Dust and Volcano Options and Emissions in WRF-Chem

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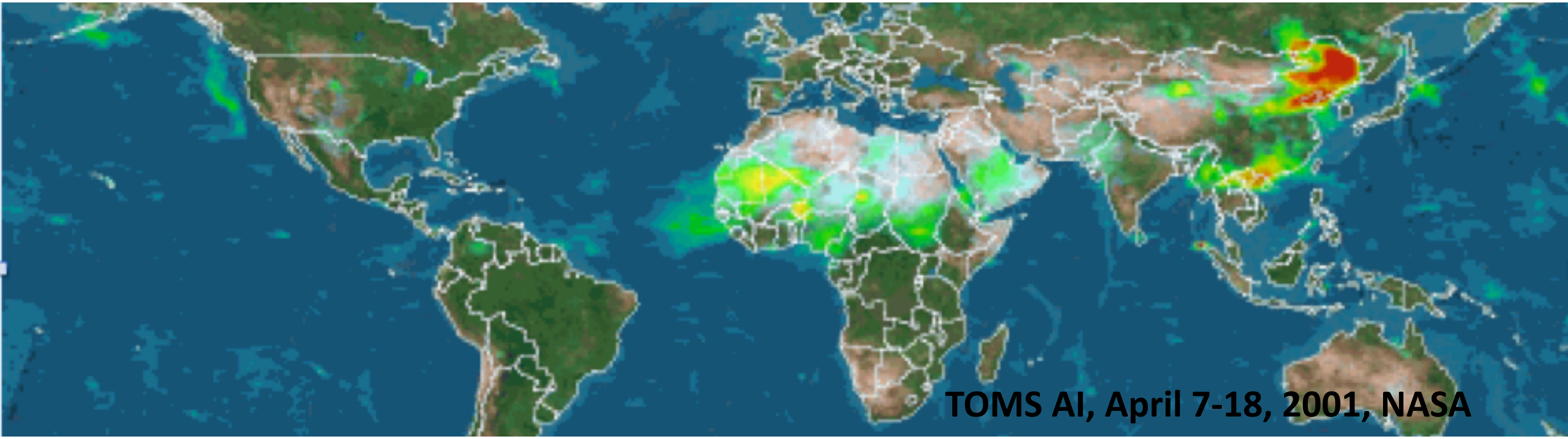
Several Dust Options in WRF-Chem
Challenges in Estimating Dust Emissions

Understanding changes in dust emissions is important for both interpreting past and predicting future climate change.



- **Large uncertainties in estimating global dust emissions that the models simulate global dust emissions between 514 and 4313 Tg yr^{-1} and dust loads ranging from 6.8 to 29.5 Tg (Textor et al., 2006; Huneeus et al., 2011).**
- **The magnitude of dust emissions to the atmosphere depends on the surface wind speed and soil characteristics, thus the spatial and temporal variability is easily influenced by changes in regional and global meteorological fields and surface properties.**
- **Incompletely understanding of the physical processes that determine the emitted dust in model, e.g., threshold fraction velocity, horizontal saltation flux and vertical flux**

Current WRF-Chem Dust Options

1. GOCART dust scheme (dust_opt= 1)

module_gocart_dust.F

2. AFWA dust scheme (dust_opt=3)

module_gocart_dust_afwa.F

3. UoC dust scheme (dust_opt=4)

dust_schme=1 (Shao 2001)
dust_schme=2 (Shao 2004, S04)
dust_schme=3 (Shao 2011, S11)
dustwd_onoff=0 (turn off Jung 2004 dust wet deposition)
dustwd_onoff=1 (turn on Jung 2004 dust wet deposition)

module_uoc_dust.F
module_uoc_dustwd.F
module_qf03.F

Dust Size Bins in WRF-Chem

radii

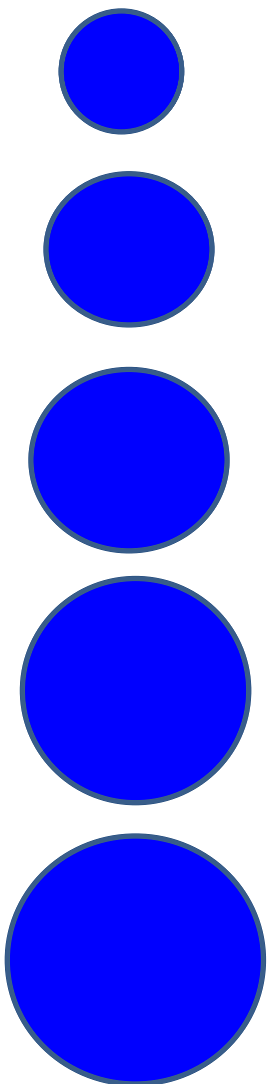
0– 1.0 µm
r-eff=0.73

1.0–1.8 µm
r-eff=1.4

1.8–3.0 µm
r-eff=2.4

3.0–6.0 µm
r-eff=4.5

6.0–10.0 µm
r-eff=8.0



Dust in WRF-Chem is distributed into 5 size bins:

Type	reff_dust(µm)	Density(kg m-3)
bin1	0.73	2500
bin2	1.4	2650
bin3	2.4	2650
bin4	4.5	2650
bin5	8	2650

- **$PM_{2.5}$=bin1+0.3125*bin2**
- **PM_{10}=bin1+bin2+bin3+0.67*bin4**

The parameters of 0.285 and 0.87 come from the linear interpolation between the range of size bins.

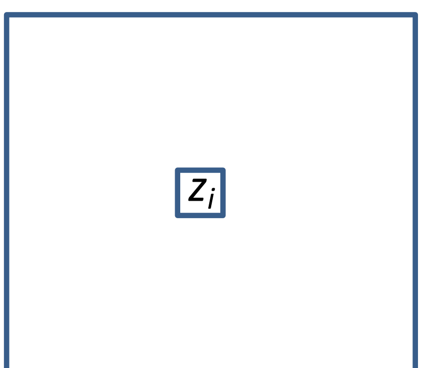
GOCART Dust Source Function *S*

- Source function *S* is the fraction of alluvium available for wind erosion, as follows:

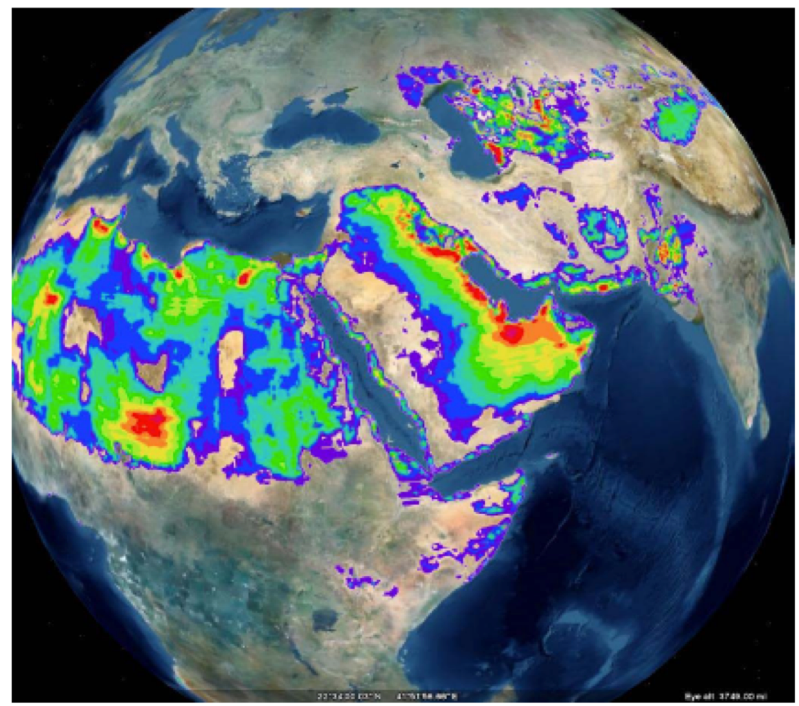
$$S = \left(\frac{z_{\max} - z_i}{z_{\max} - z_{\min}} \right)^5,$$

S: the probability to have accumulated sediments in the grid cell *i* of altitude z_i,

z_{max} and z_{min}: the maximum and minimum elevations in the surrounding 10x10 degree topography, respectively.



Ginoux Erodibility Factor



GOCART Dust Scheme

Dust uplifting flux (equivalent empirical formulation by Gillette and Passi [1998]):

Dimensional tuning constant **horizontal wind speed at 10m**

$$F_p = C_G S s_p U_{10}^2 (U_{10} - U_t^*), \quad U_{10} > U_t^*$$

Erodibility function **fraction of each size class** **threshold velocity**

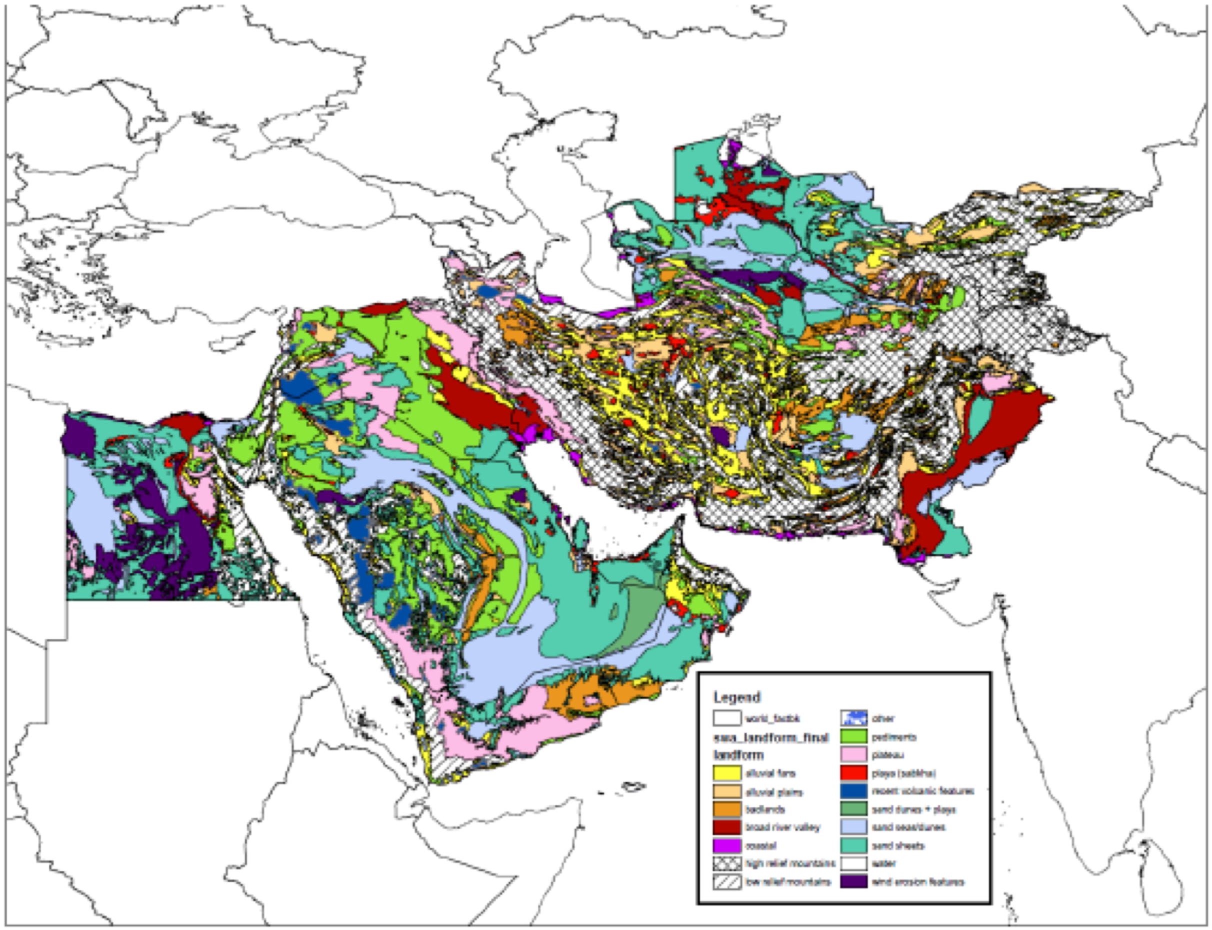
- Ginoux et al., 2001: The s_p values are thus 0.1 for the class 0.1-1 µm, and 1/3 for the classes 1-1.8 µm, 1.8-3 µm, and 3-6 µm, respectively.
- Ginoux et al., 2004: s_p values are 0.1, 0.25, 0.25, 0.25,0.25

✧ The threshold velocity (U_t^*) is actually calculate the threshold friction velocity, but they are not the same physical meaning even the same unit.

✧ U_t^* is original from Bagnold (1941) and now from Marticorena and Bergametti (1995) in WRF-Chem.

Erodibility in AFWA

Southwest Asia Landform Map (Desert Research Institute (DRI))



AFWA and DRI developing physical process based erodibility database!

Jones et al., 2012

AFWA Dust Scheme

Saltation Flux Over Bare Soil (Kawamura, 1951):

$$H(D_p) = C\frac{\rho_a}{g}{u_*}^3\left(1+\frac{u_{*_t}}{u_*}\right)\left(1-\frac{{u_{*_t}}^2}{{u_*}^2}\right) \qquad G = \sum H(D_p)dS_{rel}(D_p)$$

Using friction velocity u_* instead of using horizontal wind speed at 10m as GOCART scheme, that be consist with the threshold friction velocity u_{*t}.

Bulk vertical dust flux scheme that based on Marticorena and Bergametti (1995):

Bulk Vertical Dust Flux (efficiency factor (α): Gillette, 1979)

$$F_{bulk} = G\alpha \times \mathrm{Erod} \qquad \alpha = 10^{0.134(\%\mathrm{clay})-6}$$

- **Threshold Friction Velocity (Iversen & White, 1982)):**

$$u_{*_t}(D_p) = 0.129\frac{\left[\frac{\rho_p g D_p}{\rho_a}\right]^{0.5}\left[1+\frac{0.006}{\rho_p g D_p^{2.5}}\right]^{0.5}}{\left[1.928\left(aD_p^x+b\right)^{0.092}-1\right]^{0.5}} \qquad u_{*_t} = u_{*_t}(D_p)\,\frac{f(\mathrm{moisture})}{f(\mathrm{roughness})}$$

Jones et al., 2012

AFWA Dust Scheme

- Correction factors applied to u_{*_t},

$$u_{*_t} = u_{*_t}(D_p)\,\frac{f(\text{moisture})}{f(\text{roughness})}$$

- $f(\text{roughness})$ is a drag partition correction
  - $f(\text{roughness}) = 1.0$ implies the surface is smooth; value decreases with increasing amounts of large rocks, cobbles, vegetation, etc.
  - Currently set to 1.0; representative of Southwest Asia.
  - Dust emission is restricted to areas with roughness length $z_0 \leq 5$m (typically barren lands and sparsely vegetated surfaces).

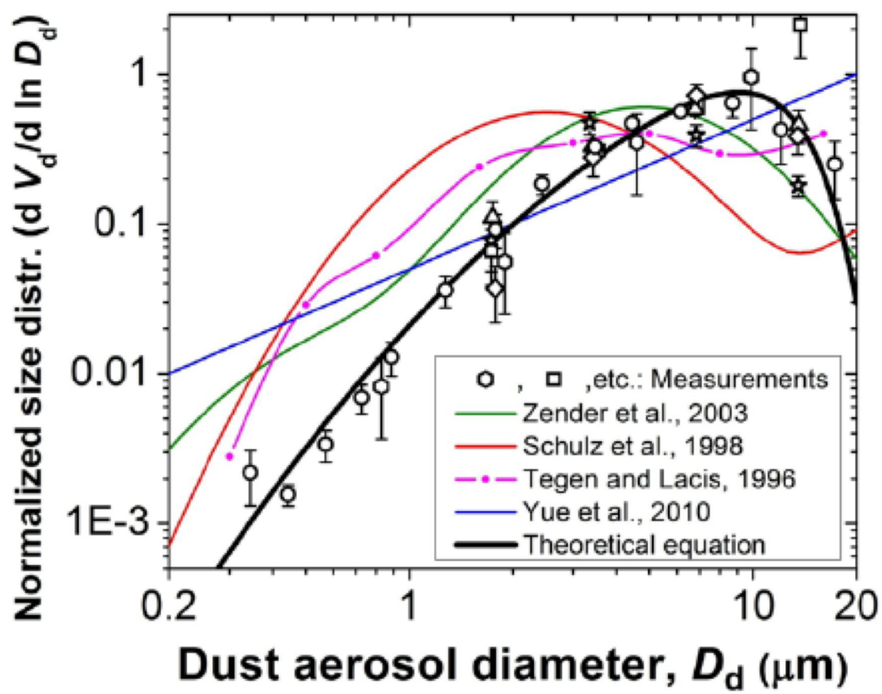
Jones et al., 2012

Dust Size Distribution in AFWA Scheme

- Marticorena and Bergametti scheme only provides bulk dust flux.
- Particle Size Distribution (PSD) developed by Dr. Jasper Kok (NCAR)
  - Brittle material fragmentation theory
  - Kok, 2010 (PNAS)

Fraction of Five Size distributions

Type	GOCART	AFWA
bin1	0.1	0.1074
bin2	0.25	0.1012
bin3	0.25	0.2078
bin4	0.25	0.4817
bin5	0.25	0.1019



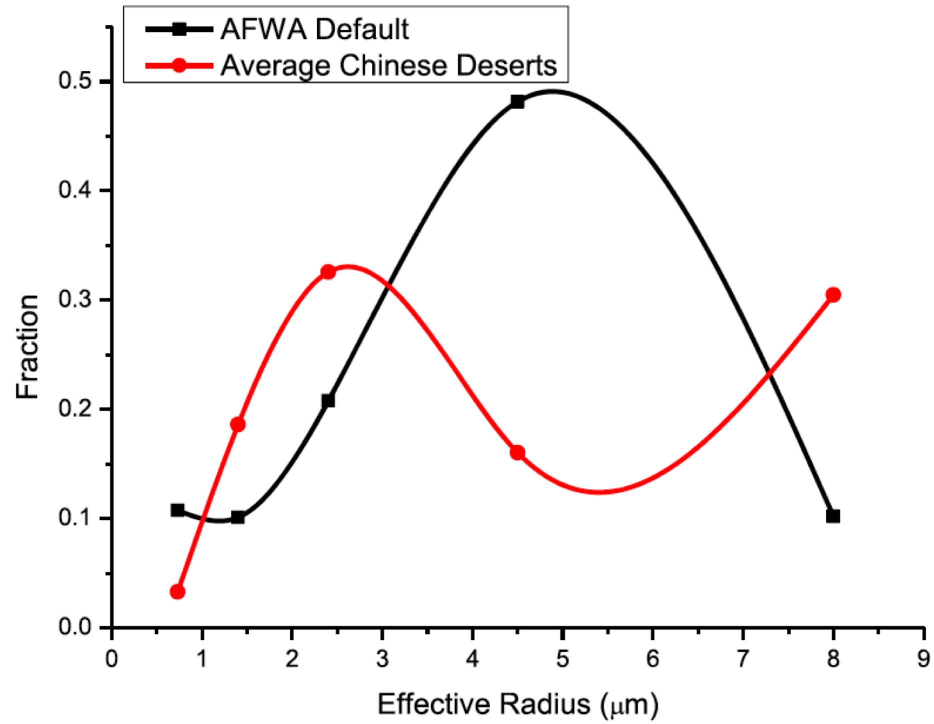
Jones et al., 2012

Dust Size Redistribution

bin1+…+bin5

Total emissions of all bins

Redistribute the emission of each size bins based on the new particle size distribution fraction.



Su and Fung 2015

For AFWA, phys/module_data_gocart_dust.F, the variable of size distribution fraction is ‘distr_dust ‘, that can be modified to your own fraction from

UOC Dust Scheme (dust_schme=2 or dust_schme=3)

Shao [2004] proposed a new size-resolved dust emission scheme (S04):

$$F(d_i, d_s) = c_y \eta_f \left[(1-\gamma) + \gamma \sigma_p\right](1+\sigma_m) g \frac{Q_{ds}}{u_*^2},$$

- $F(d_i, d_s)$: dust emission rate of size d_i generated by saltation of size d_s
- C_y: dimensionless coefficient; η_f: fraction of emitted dust
- σ_m: bombardment efficiency
- σ_p: ratio between fraction of free dust and fraction of aggregated dust
- γ: function that describes how easily aggregated dust can be released
- Q_{ds}: saltation flux of size d_s
- g: acceleration due to gravity

The erodibility factor is only used to constrain the potential emission regions instead of being used to scaling the dust emission directly as in AFWA scheme and GOCART scheme.

S04 (Shao 2004) and S11 (2011)

The emission of dust of size di associated with the saltation of all grain sizes can be estimated as a weighted average over the sand particle size range defined by d1 and d2:

$$F(d_i) = \int_{d_1}^{d_2} F(d_i; d) p_s(d) \delta d$$

Total dust emission:

$$F = \sum_{i=1}^{I} F(d_i)$$

This scheme makes use of $p_m(d)$, the minimally disturbed psd, and $p_f(d)$, the fully disturbed psd, of the parent soil to constrain the size distribution of the airborne sand and dust particles,

$$p_s(d) = \gamma p_m(d) + (1-\gamma) p_f(d)$$

The S11 scheme is a simplification of S04 with $\gamma = 1$, which means that $p_f(d)$ is no longer necessary in the simplified scheme.

Structure of the Wind erosion Scheme (S04 and S11)

1 : Input

$$u_*; p_f, p_m, u_{*p}, \theta, \lambda, c_f$$

2 : Ideal threshold friction velocity

$$u_{*t0}(d) = \sqrt{a_1\left(\frac{\rho_p}{\rho_a} gd + \frac{a_2}{\rho_a d}\right)}$$

3 : Real threshold friction velocity

$$u_{*t}(d; \lambda, \theta, s_c, s_r \ldots) = u_{*t0}(d) f_\lambda f_\theta f_{sc} f_{sr} \cdots$$

4 : Saltation flux for particle size d

$$Q(d) = \begin{cases} (1-c_f)c_o \dfrac{\rho_a}{g} u_*^3 \left(1 - \dfrac{u_{*t}}{u_*}\right)\left(1 + \dfrac{u_{*t}^2}{u_*^2}\right) & u_* \geq u_{*t} \\ 0 & u_* < u_{*t} \end{cases}$$

5 : Saltation flux Q

$$Q = \int_{d_1}^{d_2} Q(d) p(d) \delta d$$

6 : Dust emission from bin of size d_i due to saltation of grains of size d_s

$$F(d_i, d) = c_y \eta_{fi} [(1-\gamma) + \gamma \sigma_p](1 + \sigma_m) \frac{gQ(d)}{u_*^2}$$

$$\sigma_m = 12\left(\frac{u_*}{u_{*p}}\right)^2 \left(1 + 14\frac{u_*}{u_{*p}}\right) \qquad \sigma_p = \frac{p_m(d)}{p_f(d)}$$

$$F_i = \int F(d_i, d) p(d) \delta d$$

7 : Dust emission

$$F = \sum_i F_i$$

Shao et al., 2011

- Simulation of a dust storm in Australia with Shao (2004) dust emission scheme (dust_opt = 4, dust_schme = 2).

Modified from Shao (2014), PAGES Magazine, Vol. 22, No. 2.

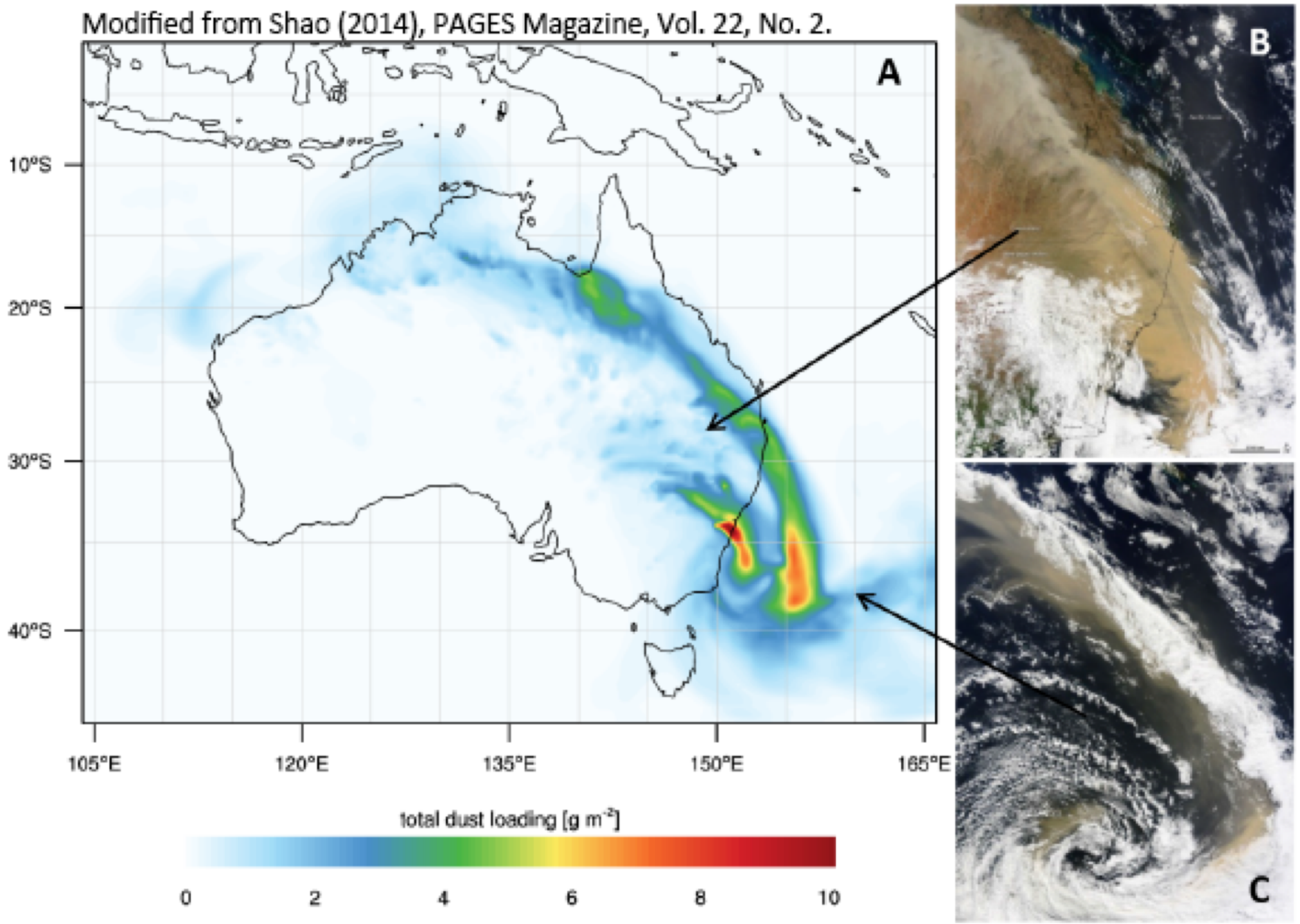


Fig. 1: (A) Dust load on 23 September 2009 modeled with WRF-Chem at 30km horizontal resolution; MODIS satellite images from (B) 23 September 2009 and (C) 24 September 2009.

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Major Dust Scheme References in WRF-Chem

dust_opt = 1 (GOCART dust emissions):

- Ginoux, P., M. Chin, I. Tegen, J. M. Prospero, B. Holben, O. Dubovik, and S.-J. Lin , 2001: Sources and distributions of dust aerosols simulated with the GOCART model. *J. Geophys. Res.,* **106(D17),** 20255-20273.

dust_opt = 3 (GOCART with AFWA modifications):

- Jones, S. L, Adams-Selin, R., Hunt, E. D., Creighton, G. A., Cetola, J. D., 2012: Update on modifications to WRF-CHEM GOCART for fine-scale dust forecasting at AFWA. *AGU Fall Meeting Abstracts*.
- Jones, S. L, Adams-Selin, R., Hunt, E. D., Creighton, G. A., Cetola, J. D., 2010: Adapting WRF-CHEM GOCART for Fine-Scale Dust Forecasting. *AGU Fall Meeting Abstracts*, Vol. 1.

dust_opt = 4 (GOCART with UoC modifications):

- Shao, Y, 2001: A model for mineral dust emission. *J. Geophys. Res.*, **106,**20,239-20,254.
- Shao, Y, 2004: Simplification of a dust emission scheme and comparison with data *J. Geophys. Res.*, **109,** doi:10.1029/2003JD004372.
- Shao, Y., M. Ishizuka, M. Mikami, J. Leys , 2011: Parameterization of size-resolved dust emission and validation with measurements. *J. Geophys. Res. Atmos.,* **116,** D08203, doi:10.1029/2010JD014527.

Volcano Options

- Chem_opt=400: Volcanic ash fall and concentration only (Simple ash treatment with 10 ash size bins)
- Chem_opt=402: Volcanic ash fall and SO_2 concentration (Simple ash treatment with 10 ash size bins and volcanic SO_2 gas emissions)
- Chem_opt=403: Volcanic ash fall (Simple ash treatment with 4 ash size bins: vash_7,vash_8,vash_9,vash_10)

Volcanic Emissions

- Emiss_opt_vol=0: no volcanic ash emissions
- Emiss_opt_vol=1: Includes volcanic ash emissions for 10 size bins
- Emiss_opt_vol=2: Includes SO_2 as well as the volcanic ash emissions for 10 size bins

Volcanic Emissions

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Also, need to turn on the io_form_auxinput=2 to include volcanic ash emissions input (wrfchemv_d01) netCDF data

Prepare Volcanic Emissions

- The volcanic ash emissions can either be for a single volcano producing just ash, or for a single volcano emitting both ash and SO_2.
- Both methods use the prep_chem_sources utility program for specifying the location of the volcano on the WRF-Chem domain and the type of emissions from the volcano.
- The prep_chem_sources includes a volcano database developed by Mastin et al.(2009), which provides 1535 volcanoes around the world and corresponding parameters (plum height, mass eruption rate, duration of eruption and the mass fraction).

Example of Mount Agung in Indonesia

- In prep_chem_srouces code, src/volc_emissions.f90

```
-8.2800,  115.1300,   2276.00, -1.,  5., 1., &! ,'BRATAN                          '&!          451
-8.2420,  115.3750,   1717.00,  1.,  6., 1., &! ,'BATUR                           '&!          452
-8.3420,  115.5080,   3142.00,  2.,  5., 1., &! ,'AGUNG                           '&!          453
-8.4200,  116.4700,   3726.00,  1.,  6., 1., &! ,'RINJANI                         '&!          454
-8.2500,  118.0000,   2850.00,  2.,  5., 1., &! ,'TAMBORA                         '&!          455
-8.2000,  119.0700,   1949.00,  2.,  3., 1., &! ,'SANGEANGAPI                     '&!          456
```

- In prep_chem_sources.inp file:

use_volcanoes=1

volcano_index =453

use_these_values='values.txt'

begin_eruption='201801290000', (begin time UTC of eruption YYYYMMDDhhmm)

Values.txt file

- **INJ_HEIGHT (meter)**
- **DURATION (second)**
- **MASS ASH (kg)**
- **MASS SO_2 (kg)**
- **Ash size distribution**

Values.txt format example:

```
11000. 10800. 1.5e10 1.5e+4
13.00 ,  20.00,  27.50, 22.50,   7.00,  4.00,   3.00,  2.00,  1.00,  0.00
```

How to get a more reasonable estimate of the above parameters?

1. News
2. References
3. Observations

Bali volcano update: Mount Agung erupts and sends huge plume of ash into sky over Bali

BALI's highest volcano erupted again today and sent a huge plume of ash 2,500m into the sky as a reminder that the danger has not yet passed.

Bali volcano update: Mount Agung sends huge plume of ash into sky - Pictures and video

Reference for Ash size distribution

```
real,parameter, dimension(5,11) :: emiss_data=RESHAPE((/&
!--------------------------------------------------------------------------------------------------------------------------
!    H km      |Duration|  Eruption   | Volume       | mass fraction   | ESP   |      Type  |  Example
! above vent   |  hr    |  rate (kg/s)|  (km3)       | < 63 micron     |       |            |
!--------------------------------------------------------------------------------------------------------------------------
       7.,        60.,      1.E+05,      0.01   ,       0.05,          &!1   M0 !Standard mafic        !   Cerro Negro, Nicaragua, 4/13/1992
       2.,        100.,     5.E+03,      0.001  ,       0.02,          &!2   M1 !small mafic        !   Etna, Italy, 7/19-24/2001
       7.,        60.,      1.E+05,      0.01   ,       0.05,          &!3   M2 !medium mafic       !   Cerro Negro, Nicaragua,  4/9-13/1992
      10.,        5.,       1.E+06,      0.17   ,       0.1  ,         &!4   M3 !large mafic        !   Fuego, Guatemala, 10/14/1974
      11.,        3.,       4.E+06,      0.015  ,       0.4  ,         &!5   S0 !standard silicic   !   Spurr, USA, 8/18/1992
       5.,        12.,      2.E+05,      0.003  ,       0.1  ,         &!6   S1 !small silicic      !   Ruapehu, New Zealand, 6/17/1996
      11.,        3.,       4.E+06,      0.015  ,       0.4  ,         &!7   S2 !medium silicic     !   Spurr, USA, 8/18/1992
      15.,        8.,       1.E+07,      0.15   ,       0.5  ,         &!8   S3 !largnvolcanoese silicic      !   St. Helens, USA,   5/18/1980

      25.,        0.5,      1.E+08,      0.05   ,       0.5  ,         &!9   S8 !co-ignimbrite silicic!   St. Helens, USA, 5/18/1980 (pre-9AM)
      10.,        0.01,     3.E+06,      0.0003,        0.6,           &!10  S9 !Brief silicic      !   Soufri�re Hills, Montserrat (composite)
       0.,        -1.,      -1.,         -1.,           -1.            &!11  U0 !default submarine    !   none
!--------------------------------------------------------------------------------------------------------------------------
        /),(/5,11/))


real,parameter, dimension(10,11) :: ash_size_dist_data=RESHAPE((/&
!----------------------------------------------------------------------------------------------------------------------------------!
! Ash bin 1       2         3       4        5       6        7        8        9      10                                         !
!----------------------------------------------------------------------------------------------------------------------------------!
         6.50 ,   12.00,   18.75, 36.25,   20.50,   3.00,    1.50,    1.00,    0.50,   0.00,  &!1    M0                            !
         0.00 ,    4.00,   10.00, 50.00,   34.00,   2.00,    0.00,    0.00,    0.00,   0.00,  &!2    M1                            !
         6.50 ,   12.00,   18.75, 36.25,   20.50,   3.00,    1.50,    1.00,    0.50,   0.00,  &!3    M2                            !
        13.00 ,   20.00,   27.50, 22.50,    7.00,   4.00,    3.00,    2.00,    1.00,   0.00,  &!4    M3                            !
        22.00 ,    5.00,    4.00,  5.00,   24.50,  12.00,   11.00,    8.00,    5.00,   3.50,  &!5    S0                            !
        24.00 ,   25.00,   20.00, 12.00,    9.00,   4.25,    3.25,    1.25,    0.75,   0.50,  &!6    S1                            !
        22.00 ,    5.00,    4.00,  5.00,   24.50,  12.00,   11.00,    8.00,    5.00,   3.50,  &!7    S2                            !
         2.92 ,    3.55,   11.82,  8.24,    7.90,  13.02,   16.28,   15.04,   10.04,  11.19,  &!8    S3                            !
         2.92 ,    3.55,   11.82,  8.24,    7.90,  13.02,   16.28,   15.04,   10.04,  11.19,  &!9    S8                            !
         0.00 ,    0.00,    0.00,  9.00,   22.00,  23.00,   21.00,   18.00,    7.00,   0.00,  &!10   S9                            !
         0.00 ,    0.00,    0.00,  0.00,    0.00,   0.00,    0.00,    0.00,    0.00,   0.00   &!11   U0                            !
!----------------------------------------------------------------------------------------------------------------------------------!
          /),(/10,11/))
!----------------------------------------------------------------------------------------------------------------------------------!
```

Major Volcano References in WRF-Chem

- *Mastin, L. G., et al. (2009), A multidisciplinary effort to assign realistic source parameters to models of volcanic ash-cloud transport and dispersion during eruptions, J. Volcanol. Geotherm. Res., 186, 10–21.*

- Freitas, S. R., Longo, K. M., Alonso, M. F., Pirre, M., Marecal, V., Grell, G., Stockler, R., Mello, R. F., Sanchez Gacita, M., 2011. PREP-CHEM-SRC 1.0: a preprocessor of trace gas and aerosol emission fields for regional and global atmospheric chemistry models. Geosci. Model Dev., 4, 419-433

Some notes

- ❑ Be careful with the dust emission unit in the output, make sure it has been multiply the grid area when calculate global total.
- ❑ When getting initial or boundary condition from other model, make sure that the dust particle size are consistent, otherwise, better to get the close fraction of dust concentrations for each size bins. The AOD calculation is very sensitive to the fraction of dust concentrations of each size bins, when compare with other model, be careful with the differences within it.

- ❖ Other questions, getting information from WRF-Chem web site: https://ruc.noaa.gov/wrf/wrf-chem/ or email group: https://ruc.noaa.gov/wrf/wrf-chem/forum.htm
- ❖ Free to contact us via wrfchemhelp.gsd@noaa.gov